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Conference paper for California State University Northridge, Northridge, California in 28 March 2012.

14. ABSTRACT
Recent advances in the development of highly conductive ionic liquids have made them of interest for use as propellant in spacecraft propulsion systems. Electrospray thrusters apply strong electrostatic fields to an ionic liquid in order to extract and accelerate charged particles/droplets, producing thrust. The behavior of these ionic liquids as they pass through the components of an electrospray system can have a significant effect on thruster operation. The wetting and adhesion behavior between the ionic liquid propellant and solid materials can be characterized using the surface tension and contact or 'wetting' angle formed when a liquid droplet comes in contact with a solid surface. Ideally this angle is a function of the interactions between the solids surface energy, the surface tension of the liquid and the interactions of both with the surrounding medium. Deviation from ideal contact angle behavior can indicate surface inconsistencies, environmental effects or contamination of the solid and liquid. Contact angle and surface tension measurements are presented for the ionic liquid propellant 1-Ethyl-3- methylimidazolium bis(triuoromethylsulfonyl)imide, called EMIIm or EtMeImTf2N, with respect to various substrate materials and environmental conditions. Analysis of these measurements determines optimum materials and operating conditions for current and future electrospray thruster designs.

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EMIIM WETTING PROPERTIES & THEIR EFFECT ON ELECTROSPRAY THRUSTER DESIGN

March 2012

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Professor Timothy Fox
Professor Sydney Schwartz
Dr. Michael Holmes

California State University Northridge: Mechanical Engineering Department
Air Force Research Laboratory: AFRL/RZSS

Introduction

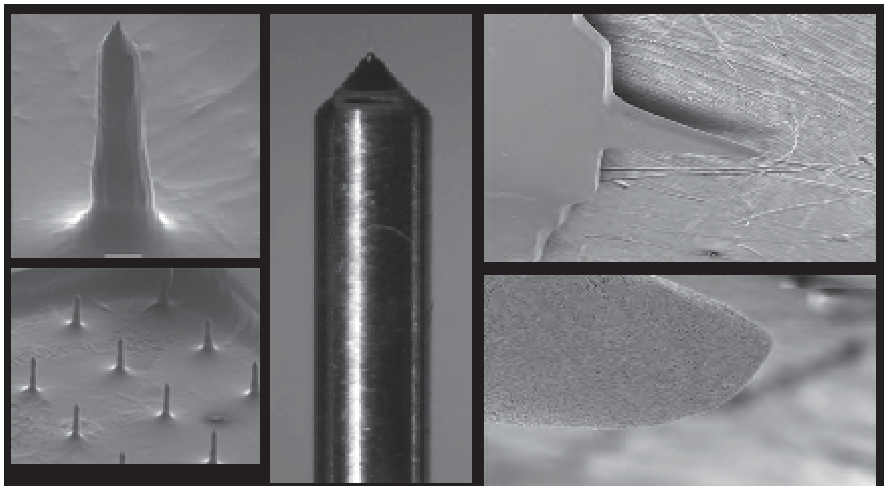
Motivation & Objective

- **Electrospray thruster for LISA Pathfinder - DRS Payload**
  - Thruster failure mechanisms identified as dependant on wetting characteristics of propellant & component materials
  - Wetting data needed to model these mechanisms & possible mitigation techniques
- **Process for measuring amount of wetting**
  - Develop ideal method for measurement
  - Determine uncertainties in measurement
  - Test other ionic liquid (IL) propellants (BMIBG4, Air Force formulations…)

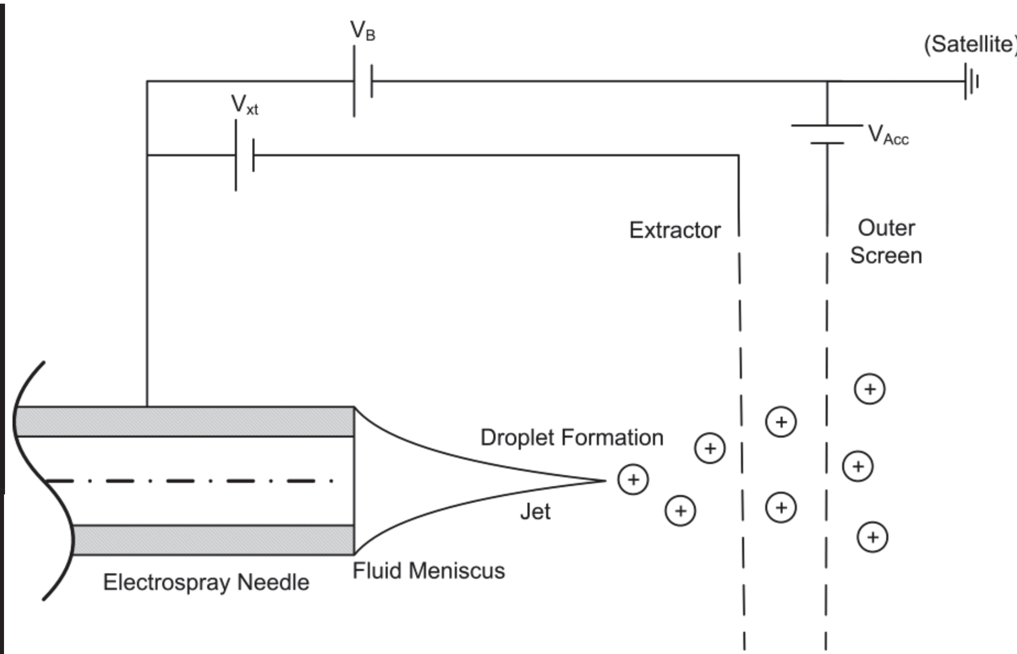
Determine amount of wetting between thruster / propellant & relationship with failure mechanisms

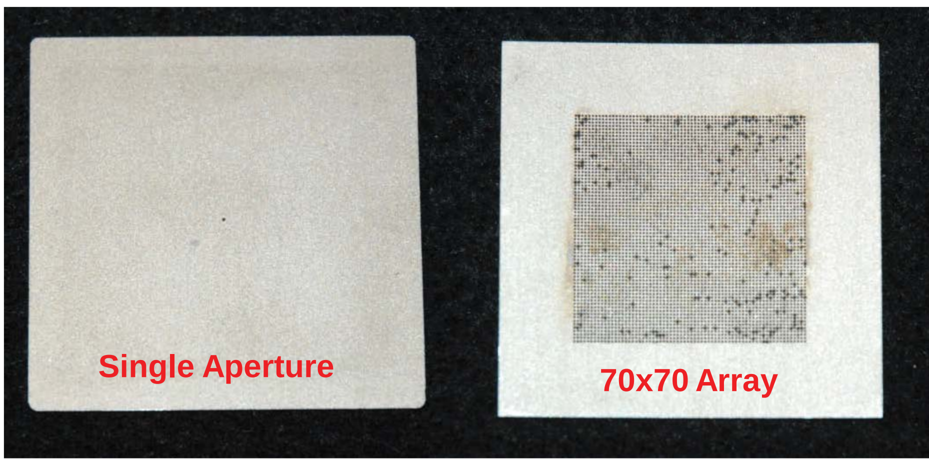
Photos Courtesy of Busek Co. Inc.

Electrosprays



- **Emitter**
  - Internally / externally wetted, porous
  - Allow propellant transport to tip





- **Extraction Grid**
  - Apply Lorentz force to propellant
  - Extract ions / droplets depending on polarity
- **Acceleration Grid**
  - Increase velocity of particles

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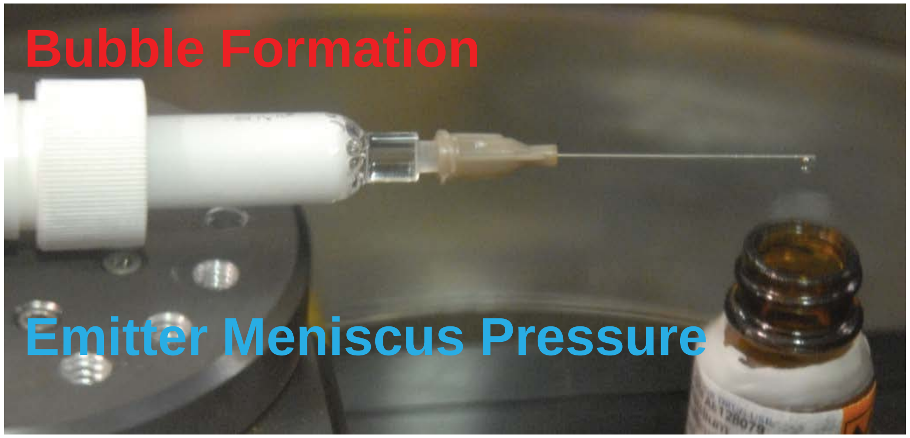
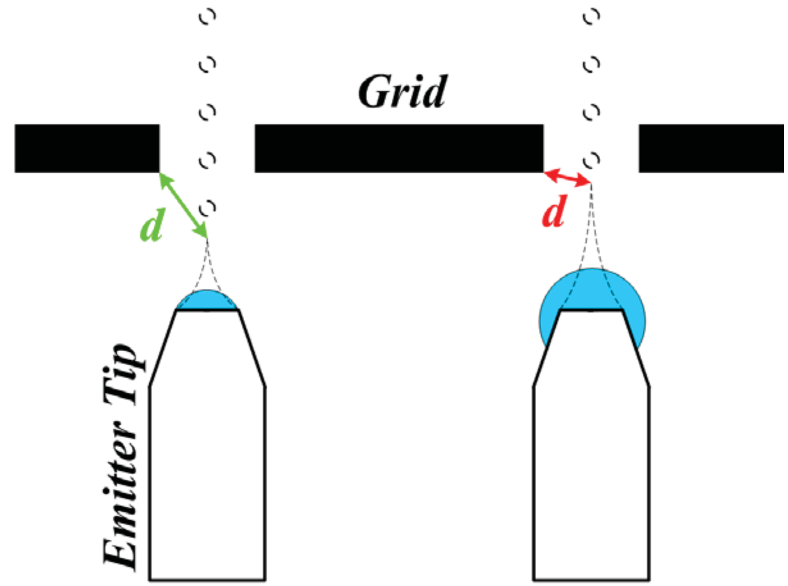
Failure Mechanisms



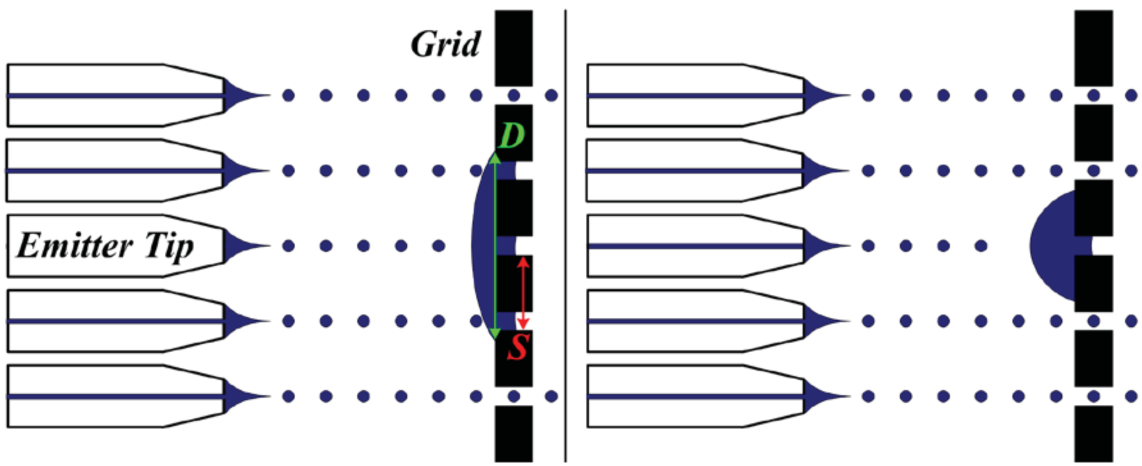


Grid Obstruction

Grid Wetting Angle

Arcing Between Grid & Emitter

Emitter Tip Wetting



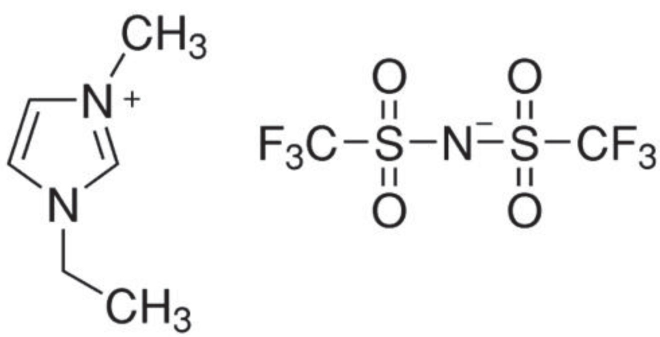
Failure Mechanism

Possible Wetting Solution

EMIIm

Electrospray Propellant

- High conductivity / charge to mass ratio
- Neglible vapor pressure
- Low Viscosity



Property	Value	Units
Density (~20°C)	1523.6	$kg \cdot m^{-3}$
Surface Tension	38.1	$J \cdot m^{-2}$
Expansion Coefficient (α_p)	$6.47 \cdot 10^{-6}$	K^{-1}
Critical Temperature	1127	K
Vapor Pressure	Negligible	-

Test Fluid

- Supplied by Strem Chemicals Inc. (CAS# 174899-82-2)
- Factory sealed with dry nitrogen
- Water content (Karl-Fischer Titration)
  - Factory Sealed Container: 2411±41 ppm
  - Waste EMIIm exposed to ambient conditions for ~8 months: 2825 ±16 ppm
  - Hygroscopic & Hydrophobic

1-Ethyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide

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Wetting Theory

Idealized System:

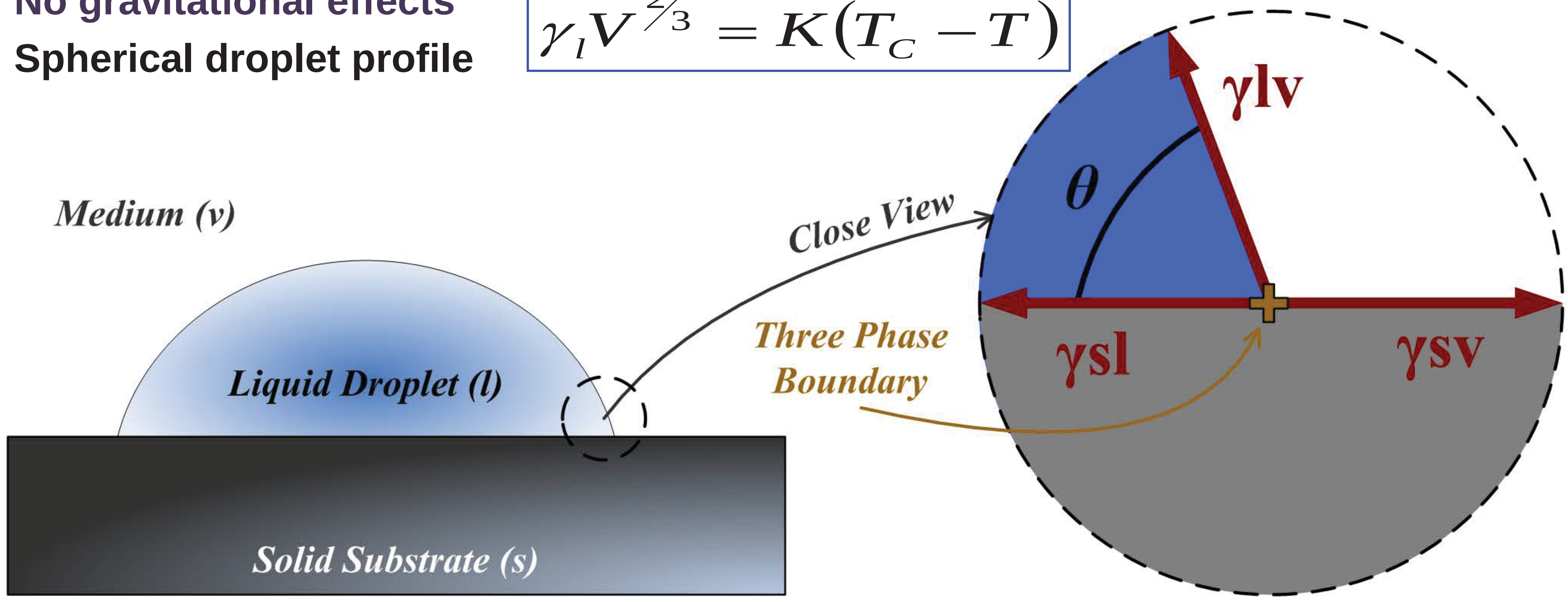
- Smooth (Ra = 0) $\boxed{Cos(\theta') = r_s Cos(\theta)}$
- No chemical Reaction, inert components
- No impurities present $\boxed{\theta' = kt^n}$
- Chemically homogeneous components
- Constant temperature/pressure
- No gravitational effects
- Spherical droplet profile

Young's Equation

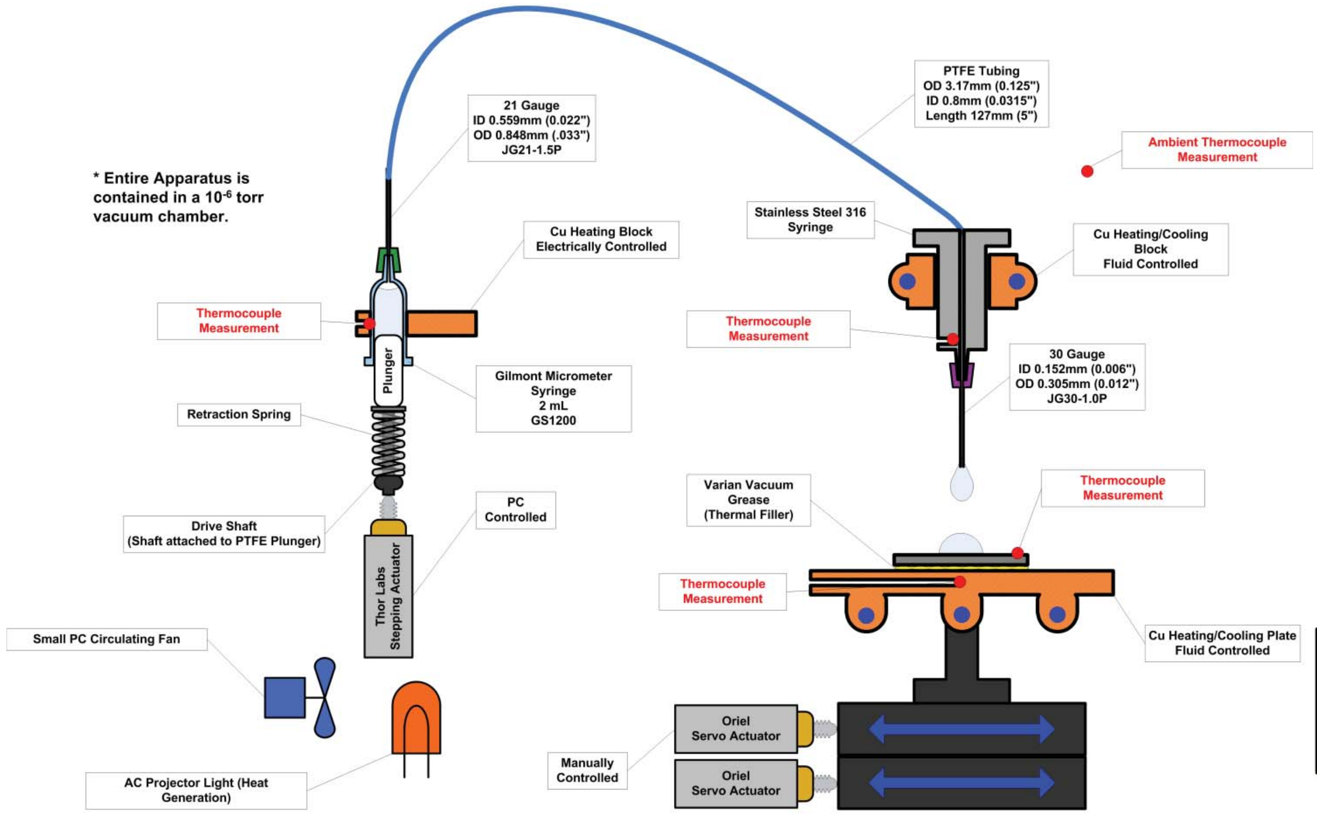
$$\boxed{Cos(\theta) = \frac{\gamma_s - \gamma_{sl}}{\gamma_l} = \frac{\pi_{sl}}{\gamma_l}}$$

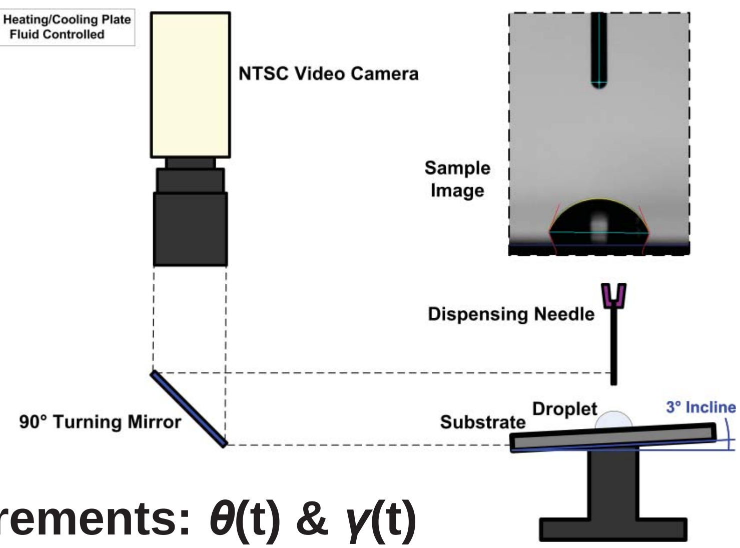
Eotvos

$$\boxed{\gamma_l V^{2/3} = K(T_C - T)}$$



Apparatus





Chamber 8, AFRL Edwards AFB

- Two stage pump train (10^{-6} Torr)

First Ten Angstroms (FTA125)

- Real time Sessile/pendant drop recording
- FTA32 analysis software, time resolved measurements: $\theta(t)$ & $\gamma(t)$

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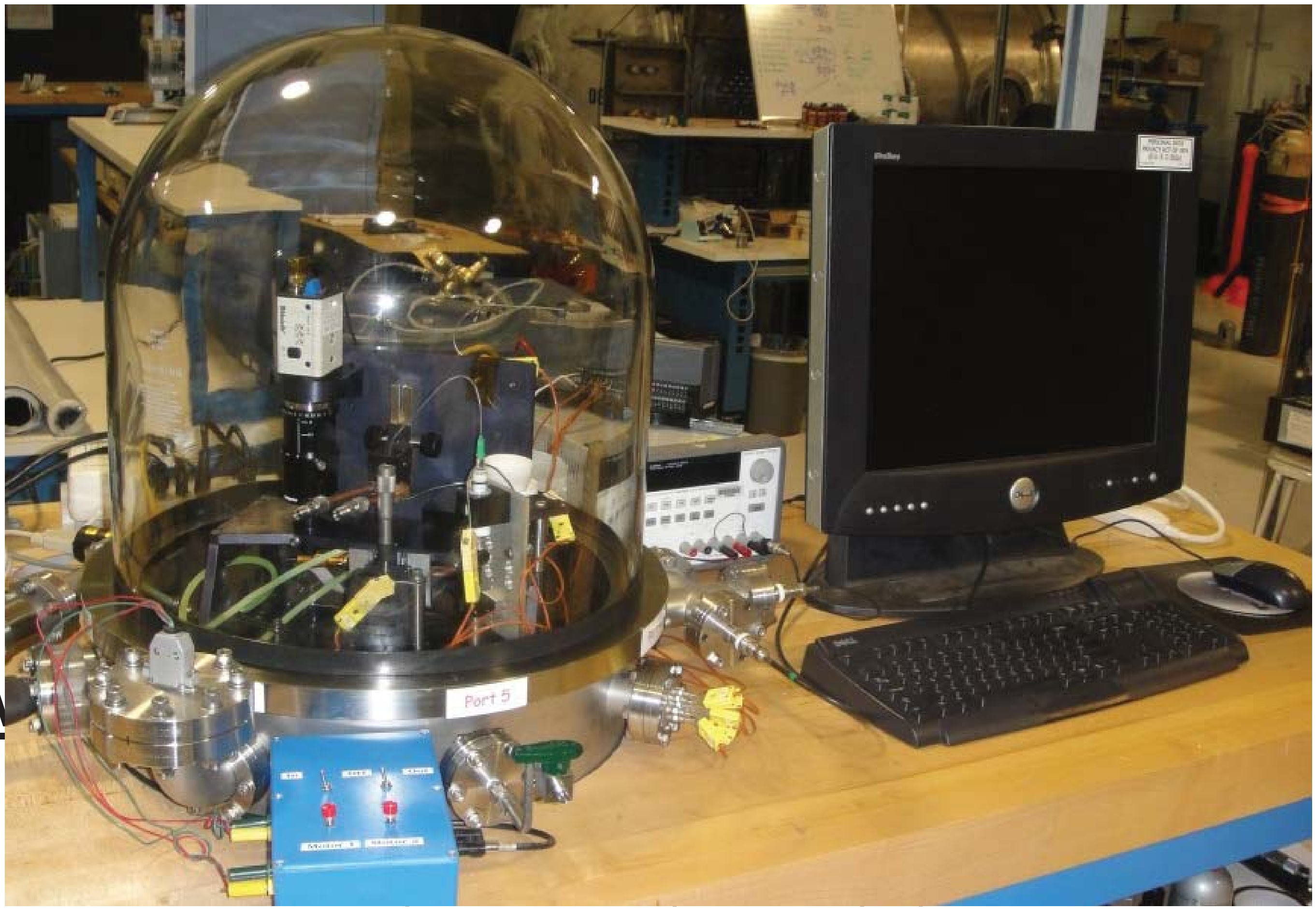
Methodology

- Simulate On-Orbit Electrospray Environment
- Determine Optimal Materials & Conditions



Surface Tension Verify System

↓

Surface Tension Temperature

↓

Surface Tension Pressure

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Contact Angle Equilibrium

↓

Contact Angle Temperature

↓

Contact Angle Pressure

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Contact Angle Advancing/Receding

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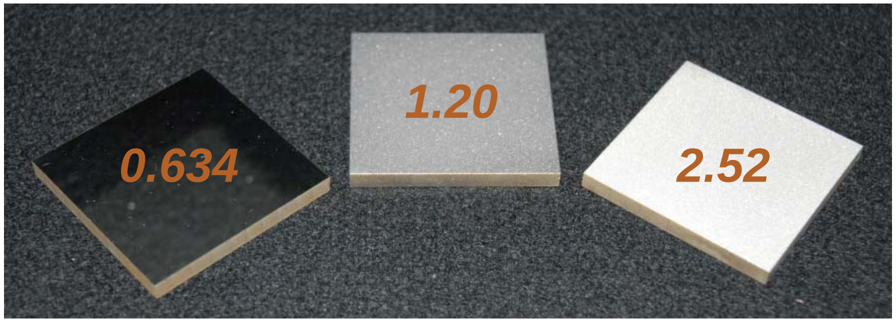
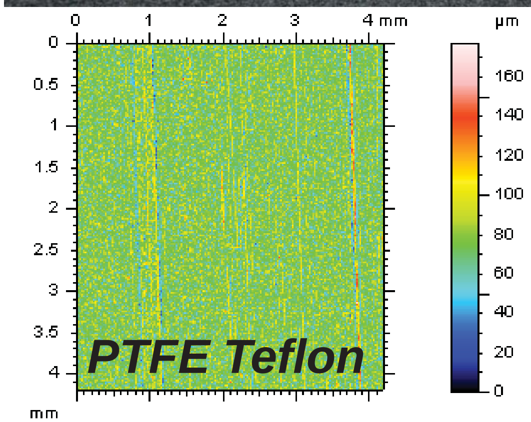
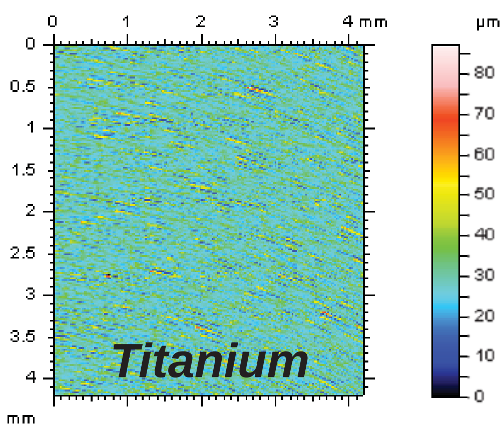
Substrates

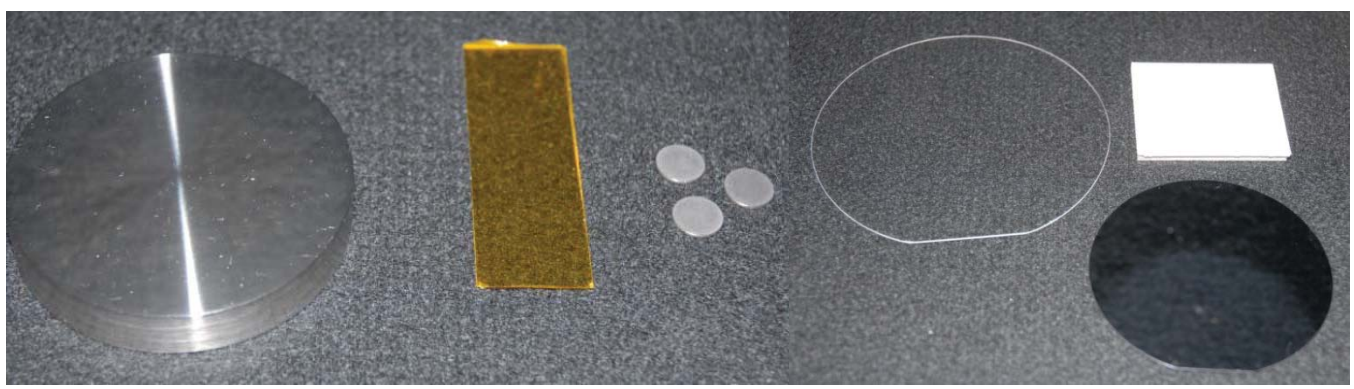


Material	Thickness (mm)	Ra (µm)
SS316	4.7	0.634/1.20/2.52
Fused Silica	0.5	< 0.144
Glass	1	< 0.144
Kapton	0.05	0.144
PTFE Teflon	1.38	1.47
Pyrex	13	< 0.144
Tungsten	1	0.351
Silicon	0.5	< 0.144
Titanium	13	0.600



- ***Ra Measured with** an* **optical laser profilometer**
- ***Limited resolution for smooth finishes***





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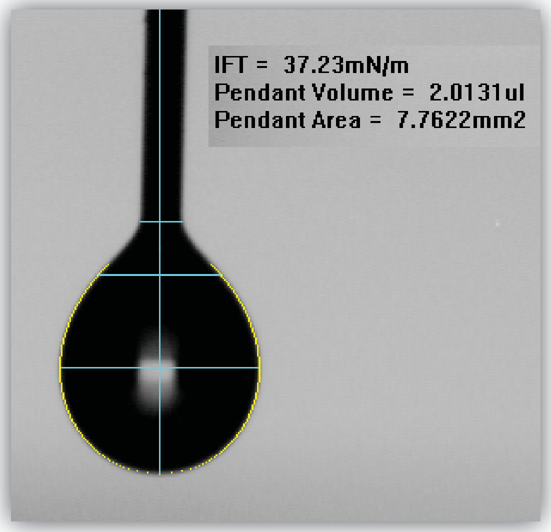
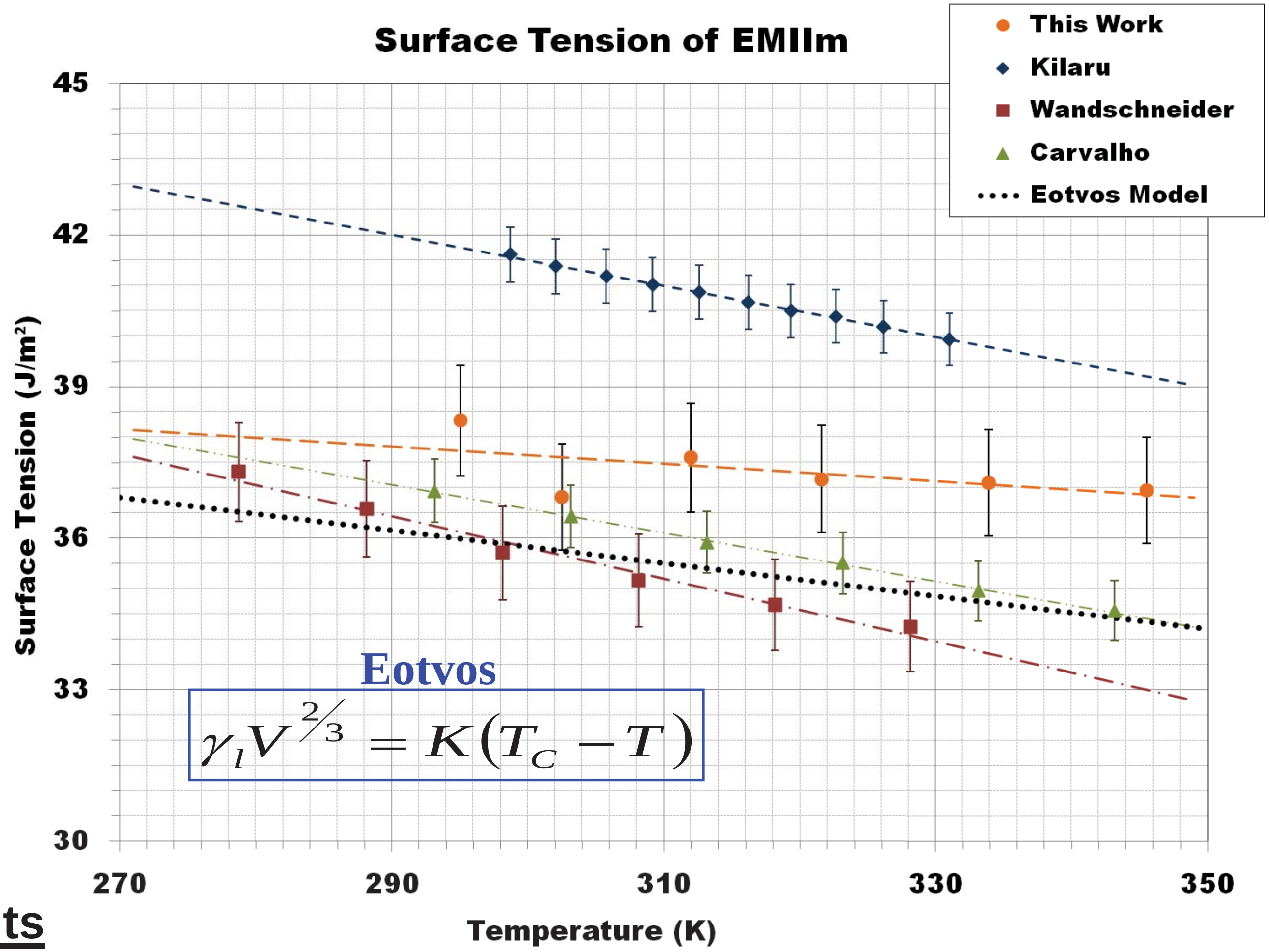
Surface Tension I



γ_l = 38.1±1.09

(~25°C, 1 ATM)



Eotvos

$$\gamma_l V^{2/3} = K(T_C - T)$$

Surface Tension (γ_l) Results

- 20 measurements taken at each temperature (T)
- Reasonable agreement with contemporary research / Model
- Decreasing γ_l as T increases » θ should decrease as well

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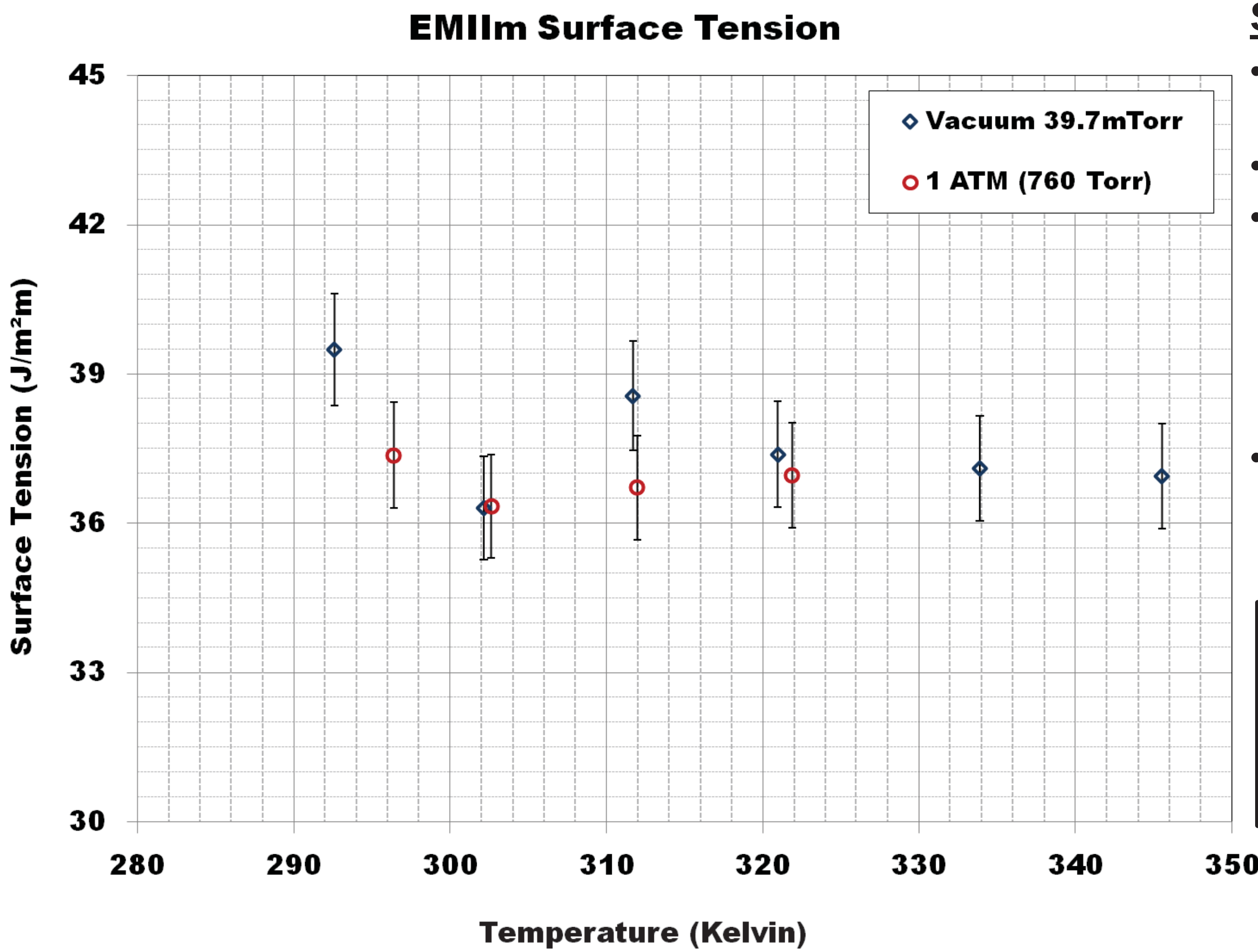
Surface Tension II



Surface Tension (γ_l) Results

- 8 measurements taken at each temperature (T) / Pressure (P)
- No meaningful trend measured
- Likely that properties change:
  - Very small change with (P)
  - Near transition state (high-T / low-P)
- Change not measurable with this apparatus

Two pressures tested:
Ambient 760 Torr
Vaccum 40 mTorr

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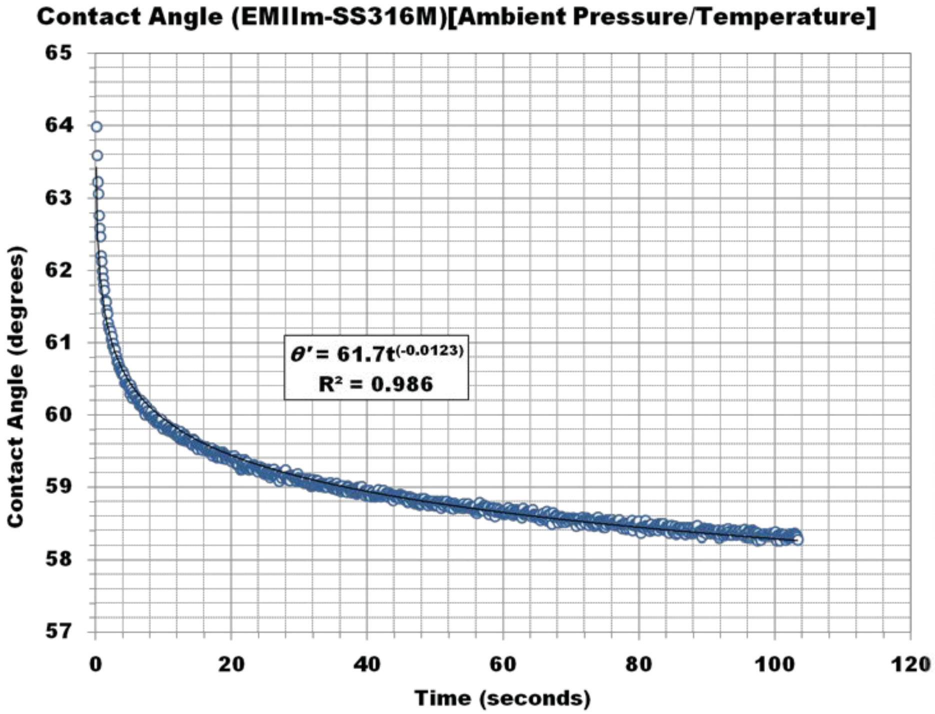
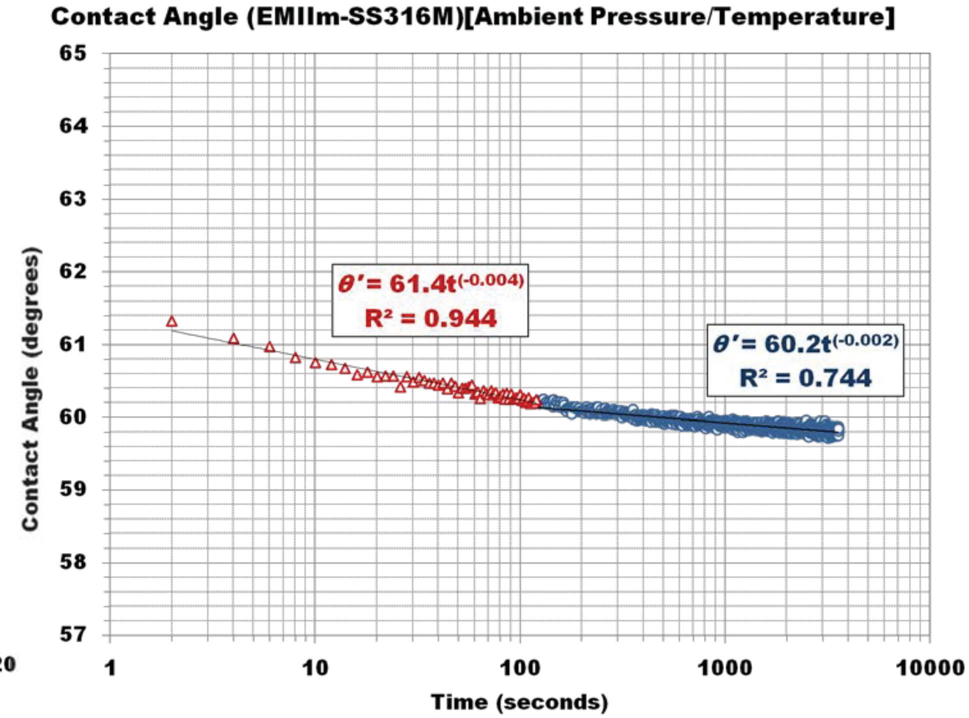
Equilibrium Contact Angles I

Dynamic Angle Behavior over Time

- Indicative of chemical reaction between component-contaminants (Marmur et. al. / Kwok)
- Unstable angle follows power law over time
- Coefficients recorded for each substrate, varying T & P
  - No measurable change in *k(T, P)* or *n(T, P)*

$$\boxed{\theta' = kt^n}$$





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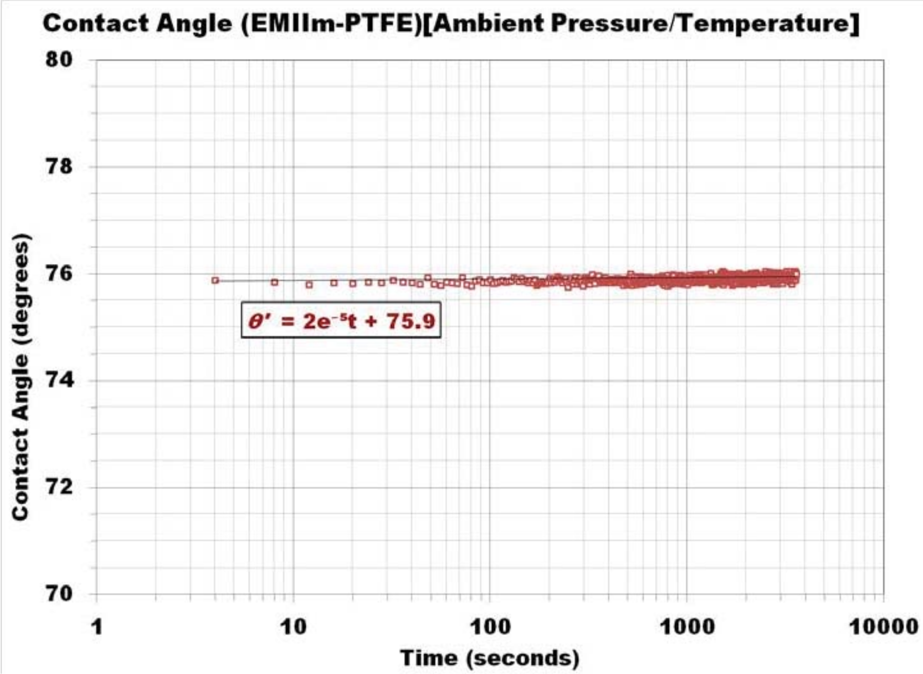
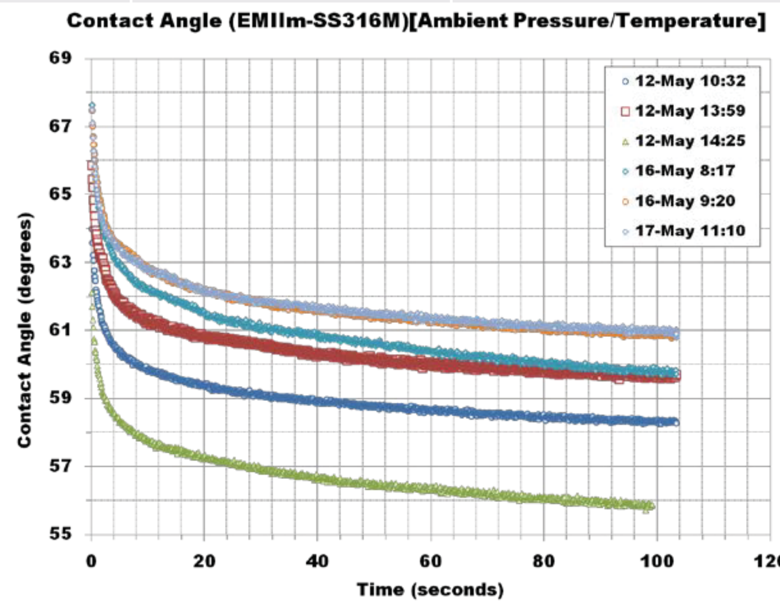
Equilibrium Contact Angles II



Material	*k*	*n*
SS316	57.2 / 60.9 / 55.1	-0.0055/-0.0104/-0.0285
Fused Silica	57.9	-0.0281
Glass	45.6	-0.0014
Kapton	59.3	-0.0079
Pyrex	45.8	-0.0336
Tungsten	39.1	-0.0015
Silicon	56.4	-0.0106
Titanium	63.2	-0.0547

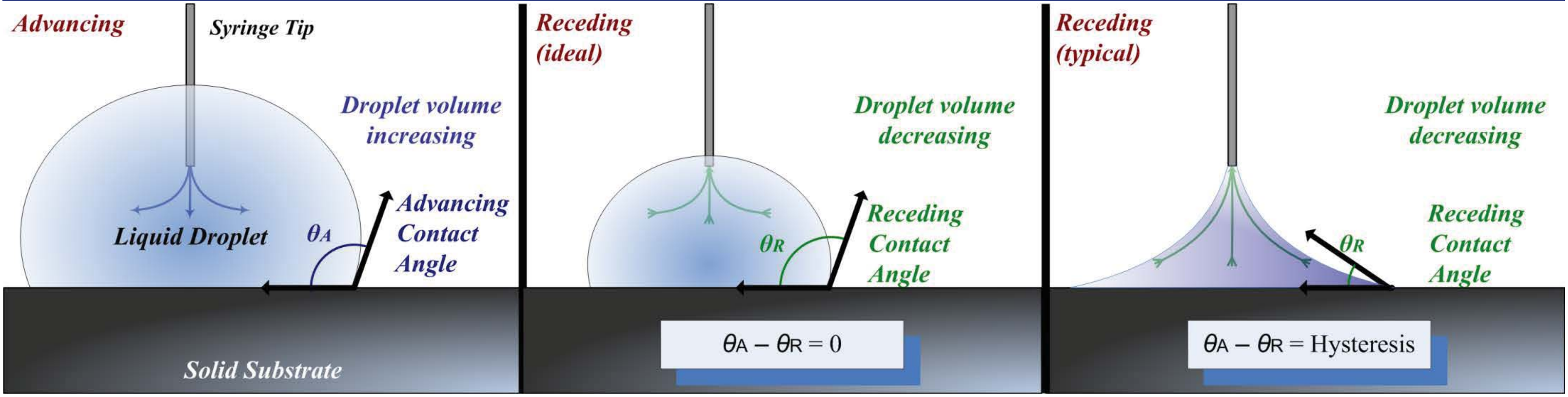
Material	*m*	*b*
PTFE Teflon	$2 \cdot 10^{-5}$	75.9

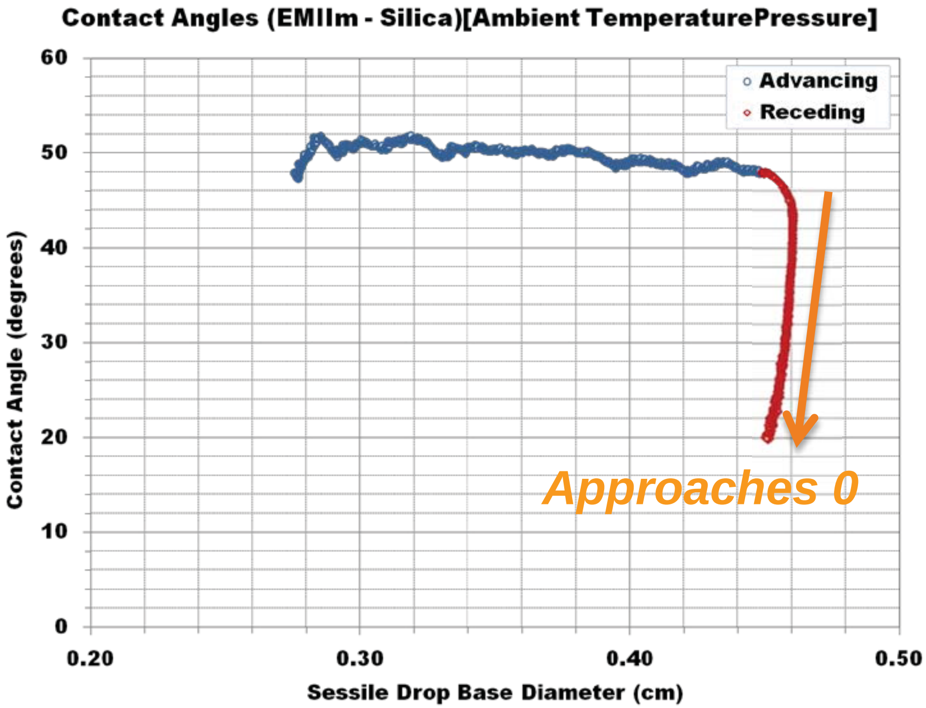


Equilibrium Contact Angle Results

- **Reaction affected each substrate except PTFE**
- ***k* appears to indicate initial contact angle**
- ***n* indicates rate of spreading**
  - **Uncertainty between data sets: ± 4°**
- **Surface roughness appears to increase wetting**

Advancing / Receding Angles I





Material	*Advancing*	*Receding*
SS316	52.1 / 58.2 / 55.9	0
Fused Silica	51.6	0
Glass	55.2	0
Kapton	52.3	0
Pyrex	49.6	0
Tungsten	43.8	0
Silicon	48.0	0
Titanium	52.3	0
PTFE	68.3	56.6

Temperature Effect

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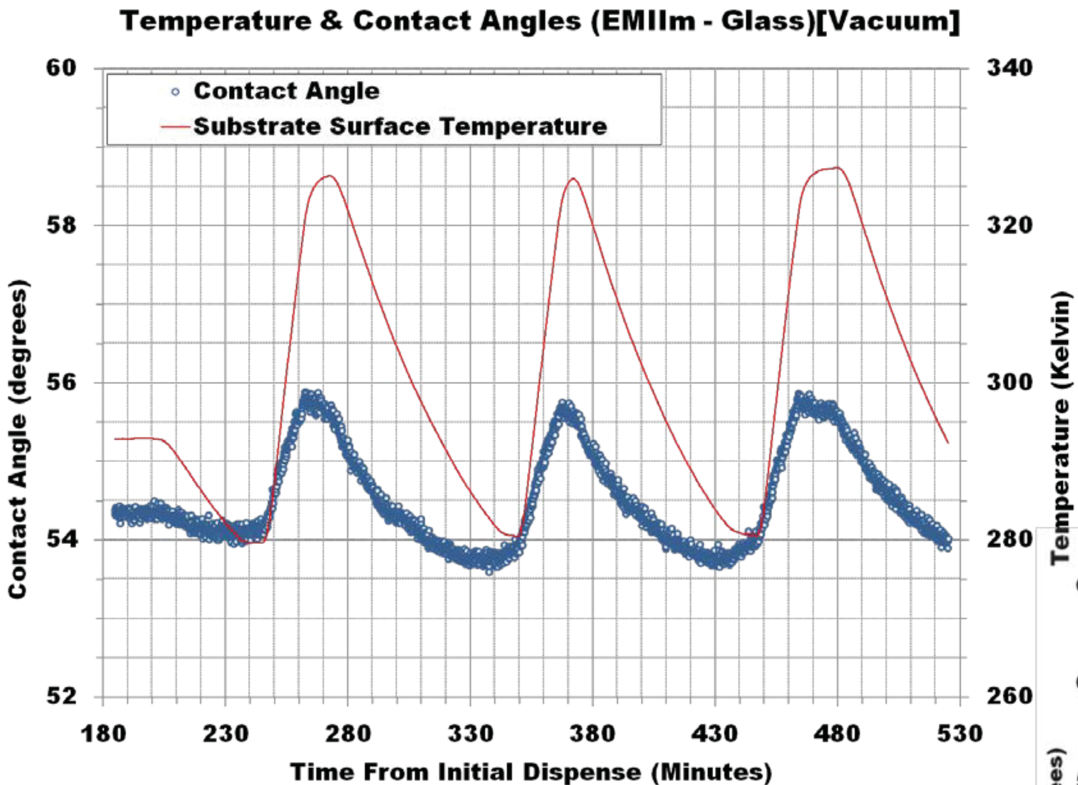
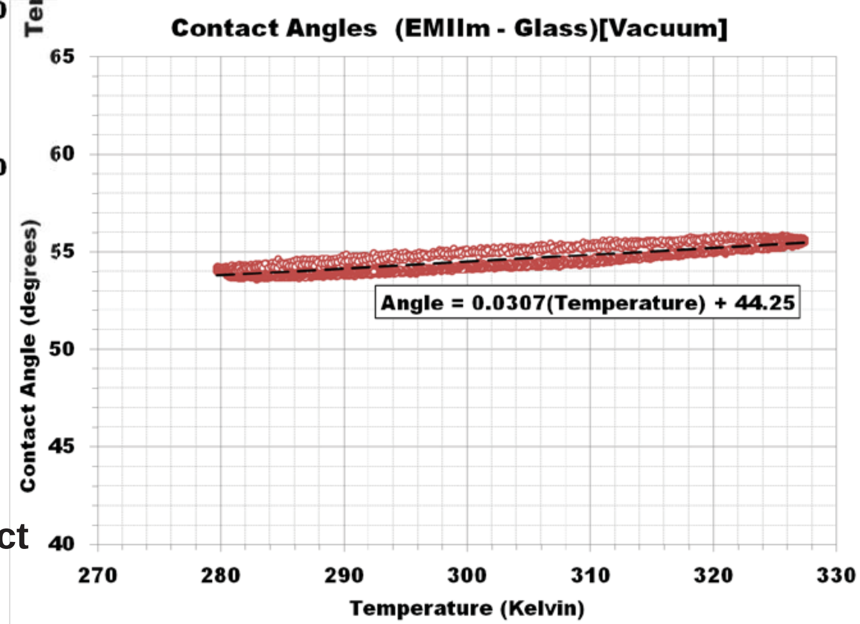


$$T\uparrow \quad \gamma_l \downarrow \quad \theta\uparrow \;\gg\; \pi_{sl}\uparrow$$

$$Cos(\theta) = \frac{\gamma_s - \gamma_{sl}}{\gamma_l} = \frac{\pi_{sl}}{\gamma_l}$$

$$\gamma_l V^{2/3} = K(T_C - T)$$



Equilibrium Temperature Effect

- Noticed over long equilibrium tests; drift in $\theta(T)$
- Substrate temperature ramp, static equilibrium droplet
  - Variation in $\theta(T)$, counter-intuitive
  - Temperature rises / Surface tension drops / Contact angle increases, greater change in adhesion tension

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Conclusions and Future Work

Conclusion

Wetting properties measured on multiple EMIIm / solid material combinations

- PTFE alone exhibits high resistance to wetting / adhesion / chemical reaction
- Pyrex / Tungsten easily wetted by EMIIm
- Increase in surface roughness appears to increase rate of wetting
- Temperature decreases surface tension, ambiguous effect on wetting due to adhesion tension of the solid

Future Work

- Repeat with other IL electrospray propellants
- Test more substrates, find a conductive solid with wetting properties similar to PTFE
- Include acid wash to clean substrate surface
- Reduce water content of EMIIm via titration process, increase accuracy
- Test EMIIm in electrospray at AFRL

Acknowledgements

- Professor Timothy Fox, California State University Northridge
- Dr. William Hargus, AFRL / RZSS Edwards AFB CA

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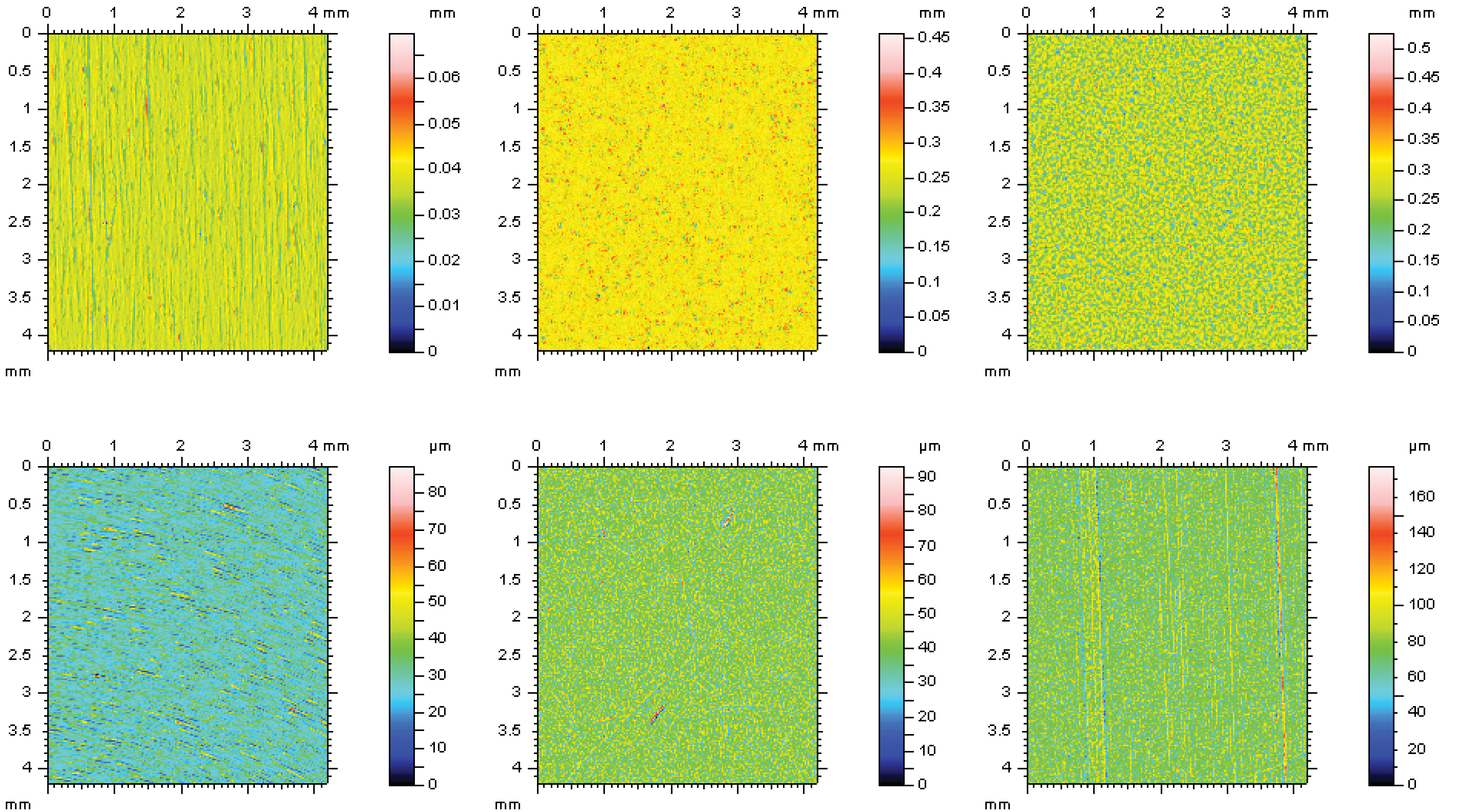
Backup Slides: Surface Roughness



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Backup Slides: 8 Hour Test